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INTERNAL BALLISTIC THEORY OF THE ONE-CHARGE, VARIABLE-VENT MORT--ETC(U)
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HDL-TR-1815—*Internal Ballistic Theory of the One-Charge, Variable-Vent Mortar,* by Edward L. Pinnes and Carl J. Campagnuolo

Internal Ballistic Theory of the One-Charge, Variable-Vent Mortar

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This paper presents a study of the interior ballistics of the one-charge mortar. The one-charge mortar is a design which was recently granted a U.S. Patent. The essential idea is of a vent of variable cross section in the mortar tube. When the projectile is fired, the vent permits part of the high-pressure combustion gases to exhaust. The area of the opening controls the muzzle velocity. This concept is believed to be an improvement over the

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design of existing mortars, such as the 81-mm mortar, where the muzzle velocity is controlled by the amount of propellant attached to the round. If a lower muzzle velocity is desired, the ammunition handler manually removes and discards the excess charges before loading. In the one-charge mortar concept, the propellant is not handled at all. Any adjustments are made by removing the lever or handle that controls the vent area.

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1. INTRODUCTION

The one-charge, variable-vent mortar, which was recently granted a U.S. Patent,[1] is shown in figure 1. In the field, the 81-mm mortar is used with any one of 10 different charge levels, denoted by the integers 0 through 9, to obtain 10 different muzzle velocities and 10 different ranges. In the variable-vent mortar analyzed here, different muzzle velocities are obtained by selecting the area of the vent through which the discharge passes, while the amount of propellant is always the same. The propellant used is M9, composed primarily of nitrocellulose and nitroglycerin.

This study is a theoretical analysis of the internal ballistics of the one-charge vented mortar. A digital computer was used to obtain results in the intended application--the 81-mm mortar. The aim of the study is twofold: first, to investigate the various physical processes involved in the firing of an open-vent mortar, and second, to obtain the information necessary for the design of the device. The design objective of the theoretical model is to determine the vent areas

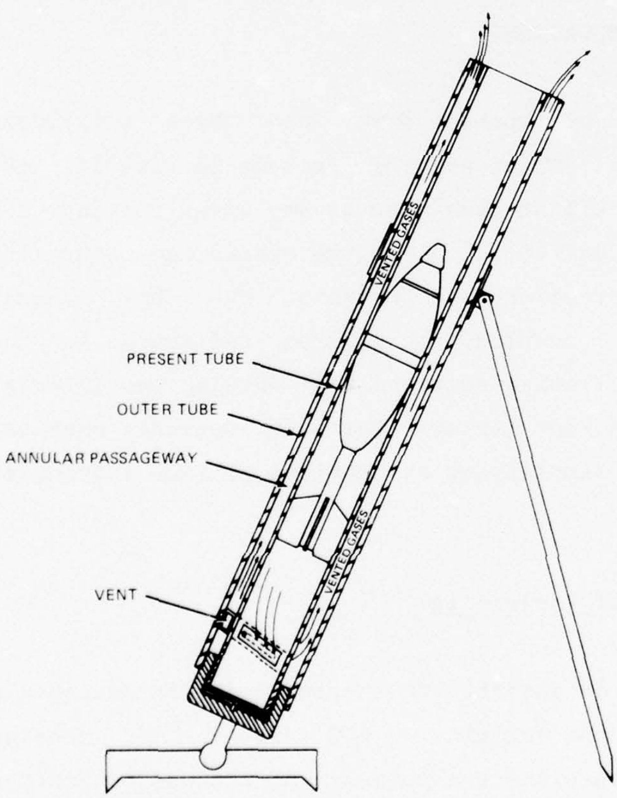

Figure 1. One-charge, variable-vent mortar concept.

[1] *Carl J. Campagnuolo and Paul A. Curto, Mortar with Variable Vent for Adjusting Velocity of a Single Charge Cartridge, U.S. Patent 3,946,637 (30 March 1976).*

for a single-charge mortar that will deliver the same explosive power on the target as the present 81-mm mortar.

With the variable-vent, single-charge mortar, there is no fundamental reason to be confined to the existing charge levels 0 through 9. However, these standard charges provide a convenient set of reference points to check the predicted values of muzzle velocity obtained with the single-charge device. The standard charge for the new system has the same mass of propellant as the present charge 9. This single charge will be referred to as the "basic charge."

2. DERIVATION OF GOVERNING EQUATIONS

The physical system can be broken down into three individual subsystems for clear analysis. These are the projectile itself, the unburned mass of solid propellant remaining at any given instant, and the hot gas instantaneously located in the volume behind the obturating band. These three will be treated one by one, but the physical phenomena are obviously all coupled, as will be reflected in the governing equations. The following sections will develop the internal ballistic theory of the open-vent mortar. The most important physical ideas will be emphasized, and simplifying assumptions will be introduced where appropriate.

2.1 Equation of Motion of Projectile

When the projectile is inserted in the tube it is assumed to be at location $x = 0$ with the velocity, $v = 0$ (fig. 2). It remains motionless until firing occurs and the pressure of the gas behind the projectile exceeds the "starting pressure," P_s. The starting pressure depends on the high initial resistance to motion of the projectile.

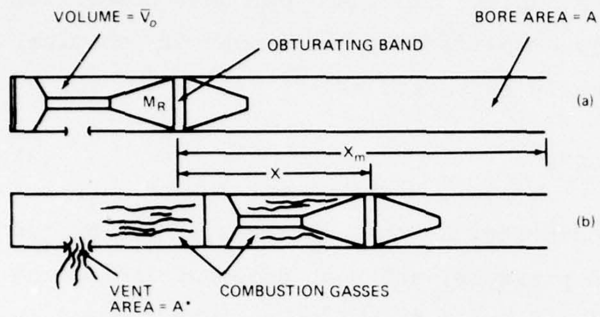

Figure 2. Schematic diagram of physical model for open-vent mortar (a) initial position, (b) projectile in motion.

Once the motion begins, the projectile is acted upon by two forces: the gas pressure acting on its base, and the bore friction acting on its circumference. The net force exerted by the gas and atmosphere is $(P - P_{atm})A$, but since $P \gg P_{atm}$, the net force can be expressed as PA. The bore friction force is customarily treated as proportional, but opposite to the pressure force exerted on the base,[1] and written as $C_f/(1 + C_f)$ PA where C_f is the coefficient of friction, having a value of approximately 0.05. Summing forces on the projectile, the equation of motion is

$$PA - \frac{C_f}{1 + C_f} PA = M_R \frac{dv}{dt} \tag{1}$$

or

$$\frac{dv}{dt} = \frac{PA}{M_R(1 + C_f)} , \tag{2}$$

$$\text{for } P \geq P_s .$$

2.2 Burning Solid Propellant

The energy source that imparts motion to the projectile is the solid propellant, which has an initial mass M_p. Once ignited, it burns continuously until it is completely consumed (i.e., $M_{pr} = 0$, where M_{pr} is the instantaneous mass of propellant remaining). The rate at which

[2] *U.S. Army Materiel Command, AMCP-706-247, Section 4, Design for Projection Ammunition Series, Engineering Design Handbook Series, Washington, DC (1964).*

the propellant burns is $\dot{m}_b$, with units of mass per unit time. The burning process is an extremely complicated phenomenon of chemical kinetics, with the burn rate normally expressed as[2,3]

$$\dot{m}_b = \rho S B P^{\alpha} \tag{3}$$

where ρ is the solid propellant density, S the surface area, B the burning rate constant, P the gas pressure, and α an exponent indicating the pressure dependence of burning rate. Actually, neither S nor B is constant,[3] but is nearly enough so that one can define a constant C_b, where $C_b = \rho SB$. Then the equation of burning solid propellant can be expressed as

$$\frac{dM_{pr}}{dt} = -\dot{m}_b = -C_b P^{\alpha} \quad (M_{pr} > 0) \ . \tag{4}$$

The accepted experimental value for α is 0.8, treated as constant although it varies somewhat with pressure.[3] The coefficient of burning, C_b, is obtained from a best fit of firing data (as is the coefficient of friction C_f).

The burning process is accompanied by a phase transformation (from solid to gas), chemical changes, and energy conversion (from chemical to thermal). The amount of energy converted per unit mass of propellant is "e." It is related to the adiabatic, isochoric flame temperature, T_v, by $e \cong c_v T_v$ (assuming constant specific heat and negligible initial thermal energy), where c_v is the constant-volume specific heat. It might be noted, however, that e is not quite constant, since the thermal energy released depends on the degree to which the chemical reaction proceeds, which in turn depends on the conditions under which combustion takes place.

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[2] *U.S. Army Materiel Command, AMCP-706-247, Section 4, Design for Projection Ammunition Series, Engineering Design Handbook Series, Washington, DC (1964).*

[3] *U.S. Army Materiel Command, AMCP-706-150, Interior Ballistics of Guns, Ballistics Series, Engineering Design Handbook Series, Washington, DC (1965).*

2.3 Combustion Gases in the Mortar Tube

The third subsystem of interest is the volume in the mortar tube, behind the obturating band, excluding the projectile itself and any unburned propellant. This enclosed volume, V, depends on the projectile position, X, and can be expressed as

$$V = V_o + AX \tag{5}$$

where V_o is the free chamber volume and A is the bore cross section.

This volume initially contains only ambient air, but at firing it quickly fills up with gaseous combustion products. Mortars generally have a low ratio of charge to projectile mass, so the gas is assumed to be uniform and have negligible velocity. The equation of state is given by the Abel equation,

$$P(V - m\eta) = mRT \, . \tag{6}$$

In this equation, η is the "covolume," defined as the volume occupied by a unit mass of gas at infinite pressure. The mass of gas instantaneously located in the tube is m; R is the gas constant, P the pressure, and T the absolute temperature. The gas is additionally assumed to have constant specific heat, so that its internal energy per unit mass is $u = c_v T$, and its enthalpy per unit mass is $h = c_p T$. The ratio c_p/c_v is defined as γ, the specific heat ratio.

The open vent in the mortar tube permits gases to discharge. Because of the high pressures in the tube, it is assumed that there is choked flow through the vent. The relation for the steady-state mass flow rate discharged from a large reservoir through a small opening, in the choked (maximum flow) condition is

$$\dot{m}_d = \frac{P_o A^*}{(RT_o)^{\frac{1}{2}}}\left[\gamma\left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma + 1}{\gamma - 1}}\right]^{\frac{1}{2}} \tag{7}$$

where P_o and T_o are the stagnation pressure and temperature in the reservoir, and A* is the vent cross section. For the mortar, quasi-steady conditions prevail, so

$$\dot{m}_d = \frac{PA^*}{(RT)^{\frac{1}{2}}}\left[\gamma\left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma + 1}{\gamma - 1}}\right]^{\frac{1}{2}} = \psi PA^*(RT)^{-\frac{1}{2}} \tag{8}$$

where P and T are the instantaneous values of chamber pressure and absolute temperature. The constant ψ is a function of γ, given by

$$\psi = \left(\gamma\left[2/(\gamma + 1)\right]^{(\gamma+1)/(\gamma-1)}\right)^{\frac{1}{2}} .$$

Equations (7) and (8) are based on isentropic, adiabatic flow from the chamber to the vent throat.

The continuity equation for the control volume can be written as the difference between the rate of production of gas by burning and the rate of discharge of gas through the vent:

$$\frac{dm}{dt} = \dot{m}_b - \dot{m}_d = \dot{m}_b - \psi PA^*(RT)^{-\frac{1}{2}} . \tag{9}$$

The energy equation for the gas is written as

$$\dot{m}_b e - PAV = \frac{d}{dt}(mu) + \dot{m}_d h . \tag{10}$$

The first term represents the rate of energy input to the gas from the combustion process. The term PAV is the rate of expansion work, which goes into kinetic energy of the round and overcomes bore friction. The first term on the right is the rate of change of total energy of the contained gas, which is equal to the internal energy, since the velocity of the contained gas is zero. The final term is the total energy efflux

of the vented discharge which is approximately equal to the enthalpy efflux, provided that the ambient temperature is small compared with the temperature T in the breech. The heat transfer from the hot gases to the gun walls has been neglected.

Expanding and substituting previous relations,

$$\dot{m}_b e - PAV = \frac{d}{dt}\left(mc_vT\right) + \dot{m}_d c_p T =$$

$$c_vT\,\frac{dm}{dt} + c_v m\,\frac{dT}{dt} + \dot{m}_d c_p T \tag{11}$$

$$= c_vT\left(\dot{m}_b - \dot{m}_d\right) + c_v m\,\frac{dT}{dt} + \dot{m}_d c_p T$$

Using $c_p = c_v + R$ and rearranging,

$$\frac{dT}{dt} = \left[\dot{m}_b\left(e - c_vT\right) - \dot{m}_d RT - PAV\right]/c_v m$$

$$= \frac{1}{c_v m}\left[\dot{m}_b\left(e - c_vT\right) - \psi A^*P(RT)^{\frac{1}{2}} - PAV\right]. \tag{12}$$

2.4 Governing Equation System and Solution Procedure

The result of the analysis is a set of five simultaneous, nonlinear, ordinary differential equations, together with the necessary auxiliary relations. The complete system is stated here.

$$\frac{dx}{dt} = v \tag{13a}$$

$$\frac{dv}{dt} = \frac{PA}{M_R\left(1 + C_f\right)} \qquad (P \geq P_s) \tag{13b}$$

$$\frac{dv}{dt} = 0 \qquad (P < P_s) \tag{13c}$$

$$\frac{dM_{pr}}{dt} = -\dot{m}_b \tag{13d}$$

$$\frac{dm}{dt} = \dot{m}_b - \psi PA^*(RT)^{-\frac{1}{2}} \tag{13e}$$

$$\frac{dT}{dt} = \left[\dot{m}_b\left(e - c_v T\right) - \psi PA^*(RT)^{\frac{1}{2}} - PAV\right]/c_v m \tag{13f}$$

$$\rho = mRT/\left(V_o + Ax - m\eta\right) \tag{13g}$$

$$\dot{m}_b = C_b P^{\alpha} \qquad (M_{pr} > 0) \tag{13h}$$

$$\dot{m}_b = 0 \qquad (M_{pr} = 0) \tag{13i}$$

The equation system is not amenable to analytical solution, so numerical methods were used. The solution procedure used was Euler's forward integration technique. This is the most basic method of forward integration, consisting of stepping in small enough steps of time (or, in general, the independent variable) so that each derivative can be considered constant over the interval. Each dependent variable is evaluated at each step by the algorithm $f_{K+1} = f_K + (df/dt)t$. The solution begins from the initial conditions of motion. The initial values for travel and velocity are zero, and the chamber is considered to be filled with air at ambient temperature and pressure. At t = 0 propellant burning is initiated, and the solution continues, stepwise, until the travel exceeds the muzzle length, indicating that the projectile has exited and begun free flight. The procedure was programmed in FORTRAN and executed on the HDL IBM 370. The program and sample output are given in appendix A.

3. RESULTS

3.1 Description of 81-mm Mortar

The general system of simultaneous, nonlinear, ordinary differential equations was solved for the 81-mm mortar with the M374 or M375 projectile. The equations were solved for a one-charge mortar designed to have the same range and deliver the same explosive energy on the target as the 81-mm mortar. The physical dimensions therefore were selected to accommodate a projectile of the same mass as the 81-mm projectile so that the muzzle velocity obtained with the vent completely closed would be the same as the muzzle velocity of the 81-mm mortar when fired at charge 9, which gives the maximum range. The solution of the equations gave the vent areas needed to produce the same muzzle velocities that would be attained by the 81-mm projectile fired at the other charge increments.

The relevant physical dimensions of the mortar and projectile were obtained from Heppner[4] and the thermodynamic properties of the propellant gas came, directly or indirectly, from AMCP-706-247.[2] They are presented in table I.

Other physical quantities needed for the calculations were not available in the literature, and had to be estimated. The coefficient of friction, C_f, and the burning constant, C_b, were not found in the literature. To obtain values for these coefficients, the system of equations was solved for the closed-vent case, $A^* = 0$, by use of various combinations of C_b and C_f. The solutions were identical in shape to the

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[2] *U.S. Army Materiel Command, AMCP-706-247, Section 4, Design for Projection Ammunition Series, Engineering Design Handbook Series, Washington, DC (1964).*

[4] *Leo D. Heppner, Final Report on Special Study of Setback and Spin for Artillery, Mortar, Recoilless Rifle, and Tank Ammunition, Aberdeen Proving Ground (1968).*

curves in Heppner's report.[4] The values of C_b and C_f were found by requiring that the muzzle velocity and peak pressure simultaneously agree with the experimental values for closed-vent firings. For closed vent area at charge 9, values for C_b and C_f were found to be

$$C_b = \left(27.5 \times 10^{-6} \text{ kg/s}\right) P^{0.8}$$

$$C_f = 0.055 \ .$$

Slight changes in the above values do not appreciably influence the correspondence between experimental and calculated results.

TABLE I. PHYSICAL QUANTITIES USED IN ANALYSIS

81-mm Mortar		
A	Bore area	52.06 cm² (8.07 in.²)
X_m	Muzzle length	83.3 cm (32.8 in.)
V_o	Chamber volume	1032. cm³ (63 in.³)
M374/375 Projectile		
M_R	Mass of projectile	4.136 kg (9.12 lbm)
P_s	Starting pressure	700 kPa (100 psi)
M9 Propellant: Gaseous Combustion Products		
mol wt	Molecular weight	27.63
γ	Specific heat ratio	1.2102
R	Gas constant	301 J/kg-K
c_v	Specific heat	1432 J/kg-K
c_p	Specific heat	1733 J/kg-K
η	Covolume	938.2 cm³/kg
e	Energy "release"	5.44×10^6 J/kg
T_v	Flame temperature	3799 K

The given value of friction coefficient is expected to be valid whenever the present mortar-projectile combination is used. However, C_b must be reevaluated for each different quantity, composition, or shape of propellant used. The above value applies only to the basic charge 9. It is assumed that an open vent does not alter

[4]*Leo D. Heppner, Final Report on Special Study of Setback and Spin for Artillery, Mortar, Recoilless Rifle, and Tank Ammunition, Aberdeen Proving Ground (1968).*

C_b, although it is possible that the modification in internal flow may do so to a slight extent.

3.2 Results for Basic Charge 9

Using the values of C_b and C_f thus obtained, one can solve the system of equations to obtain round muzzle velocity as a function of vent area. This information is necessary to design the vent, and is presented graphically in figure 3. At $A^* = 0$, the muzzle velocity has its closed-breech value of 261 m/s (856 fps), and decreases with increasing vent area. The curve tends to become flatter at lower muzzle velocities. The curve is not extended past $A^* = 15$ cm^2 (2.3 in.^{2}), for reasons that will be explained later.

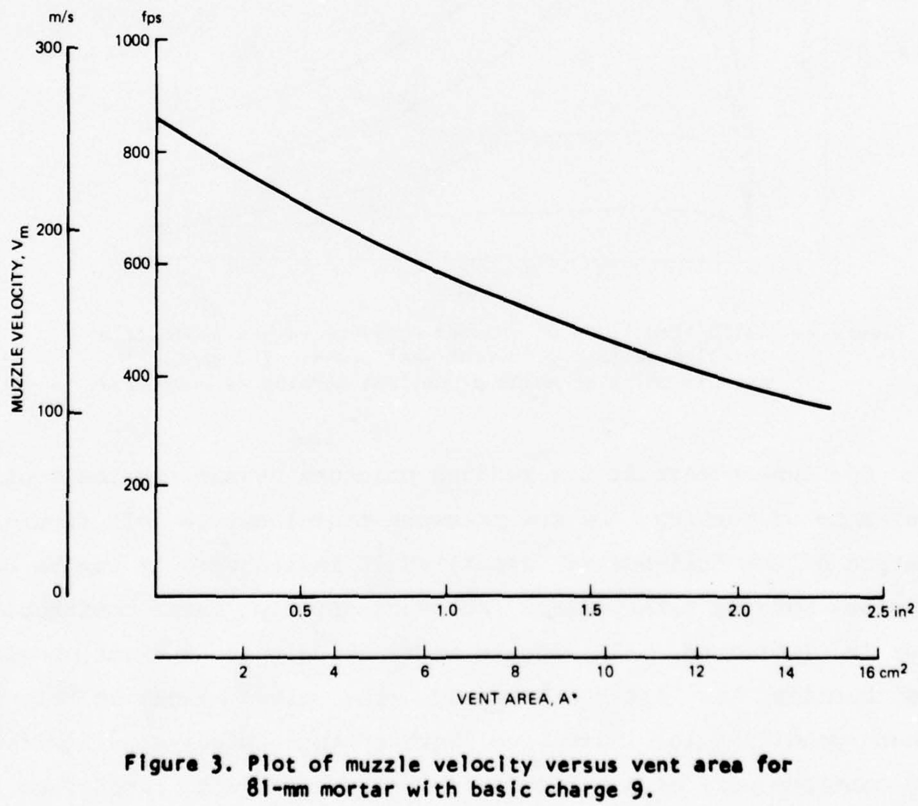

Figure 3. Plot of muzzle velocity versus vent area for 81-mm mortar with basic charge 9.

As the projectile moves along the tube, the base pressure is varying rapidly. Figure 4 is a plot of base pressure versus projectile travel for several vent areas. The uppermost curve applies to the closed breech case, having a peak pressure of 57 MPa (8,300 psi). Three other curves are shown, for vent areas of 3.1, 8.7, and 14.8 cm^2. The presence of an open vent not only decreases the pressure at every point, but also has the effect of flattening the curve, yielding a less pronounced peak.

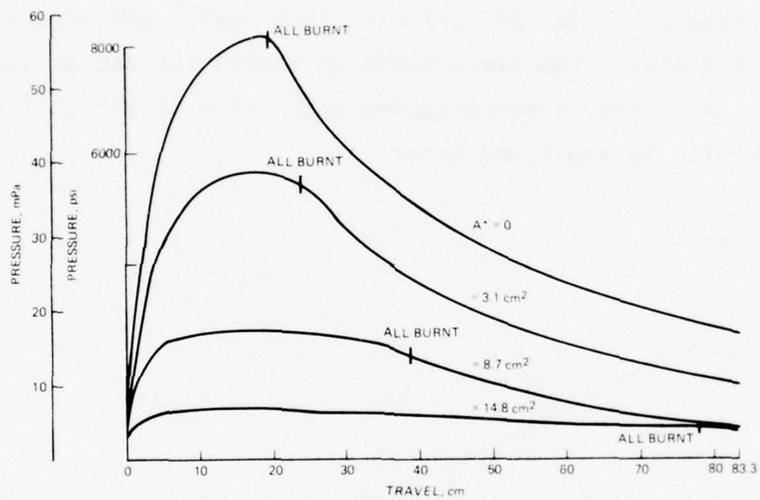

Figure 4. Calculated plots of chamber pressure versus projectile location at four different vent areas. The vertical mark is point at which propellant burning is completed.

One consequence of the reduced pressure caused by the vent is a slower rate of burning. On the pressure-travel curves of figure 4, the location of the "all-burned" condition is indicated. It can be seen that complete burning takes place at successively later positions as vent area is increased. It should be recalled that an exact model to describe burning has not been devised. The given location of the all-burned condition is indicative rather than precise. In fact, burn out consists more of a "fizzle out" than an abrupt cutoff, as the last bits of propellant are consumed.

Figure 5 is an aid for understanding the problem of large vent areas. For each vent area, two elapsed times are plotted: the lower curve is the elapsed time between initiation and completion of burning. The upper curve represents elapsed time between initiation of burning to round muzzle exit. For small vent areas, it can be seen that burning is completed before the projectile exits the gun, which is desirable. However, the two curves appear to intersect near A* = 15.5 cm^2. This means that for large vent areas, apparently, the reduced pressure causes a rate of burning so slow that the round exits from the muzzle while some propellant is still unburned. This condition may increase muzzle blast and may cause some irregularity in muzzle velocity at the equivalent zero charge. For this reason the present study recommends an upper limit of 15 cm^2 (2.3 $in.^2$) on the vent area.

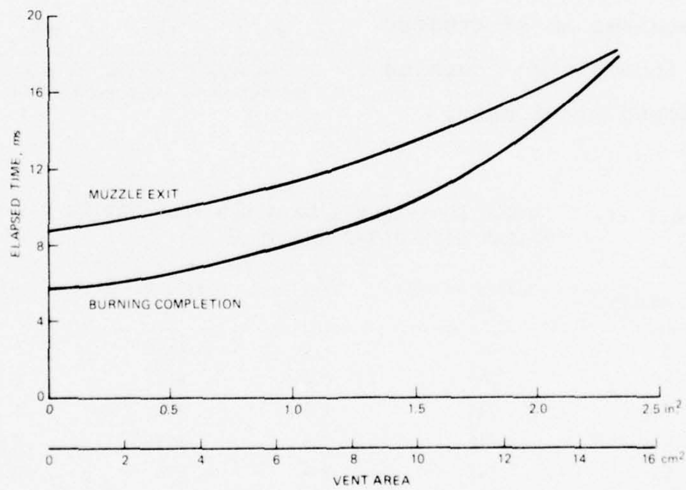

Figure 5. Comparison between elapsed time to burning completion and elapsed time to muzzle exit, versus vent area, for 81-mm mortar with basic charge 9. Elapsed times begin from initiation of burning.

The purpose of the variable vent is to provide different muzzle velocities, without the problems of manually removing solid propellant charges. Therefore, it is convenient to know what vent area is necessary to simulate each of the charge levels currently in use.

The current charge levels are listed in table II, and the single-charge mortar "charge equivalents" are given in table III. The charge equivalent is the standard charge level which would yield the same muzzle velocity in a closed-breech mortar. Since this study assumes all rounds contain charge 9 (0.1058 kg of M9 propellant), A* = 0 has a charge equivalent of 9. There appears to be no problem in obtaining muzzle velocities corresponding to charges 1 through 9. The muzzle velocity corresponding to charge 0 requires an A* greater than the incomplete burning problem mentioned previously.

TABLE II. CHARGE LEVELS CURRENTLY USED IN 81-mm MORTAR WITH M374/375

Charge Number	Muzzle velocity m/s	Muzzle velocity ft/s	Mass of propellant, kg
9	261	856	0.10582
8	248	814	0.09503
7	233	764	0.08419
6	216	709	0.07335
5	197	646	0.06255
4	176	577	0.05176
3	154	505	0.04091
2	132	433	0.03007
1	104	341	0.01928
0	64	210	0.00744

Excerpt from Final Report by Leo D. Heppner, Aberdeen Proving Ground (1968).

TABLE III. CHARGE EQUIVALENTS OBTAINED FROM VARIABLE-VENT MORTAR WITH BASIC CHARGE 9

Charge equivalent	*Muzzle velocity* m/s	*Vent area* cm^2	*Muzzle velocity* ft/s	*Vent area* $in.^2$
9	261	0	856	0
8	248	0.85	814	0.13
7	233	1.9	764	0.29
6	216	3.1	709	0.48
5	197	4.6	646	0.71
4	176	6.5	577	1.01
3	154	8.7	505	1.35
2	132	11.2	433	1.74
1	104	14.8	341	2.29
0	64	21.0	210	3.25

Table IV shows the peak pressure and temperature occurring within the mortar tube. As expected, the extreme values occur for closed-breech firings, when there is no venting of the hot gases. It is

TABLE IV. COMPARISON OF PEAK PRESSURES AND TEMPERATURES IN VENTED AND CLOSED-BREECH SYSTEMS

Charge or charge equivalent	Peak pressure, closed-breech[a] MPa	Peak pressure, vented mortar[b] MPa	Peak temperature, closed breech[c] K	Peak temperature, vented mortar[b,c] K
9	57(57)	57	3617	3617
8	52(50)	51	-	3592
7	45(43)	45	-	3561
6	38(37)	38	3574	3526
5	31(30)	31	-	3486
4	25(24)	24	-	3438
3	19(18)	18	3447	3387
2	14(14)	12	-	3335
1	11(13)	7	3252	3272
0	6(12)	3	-	3190

[a] *In this column, the first value is from Leo D. Heppner, Aberdeen Proving Ground Final Report (1968), and the value in parentheses is from Aberdeen Proving Ground MTP4-2-012 (1971). The authors do not know why the discrepancy appears at the lower charges.*

[b] *Computations of the values for the vented mortar were based on the internal ballistic theory of this paper.*

[c] *Tabulated values were not available, so these values were obtained theoretically. Since the theoretical model did not include heat transfer, the magnitudes given for temperature are probably somewhat high. They should be used for comparison purposes only.*

interesting that, for each charge equivalent, the peak pressure attained is roughly equal to that with the equivalent smaller charge in a closed-breech weapon. Hence, the mechanical stress in the one-charge system will be no different from that existing in the present system.

Additional calculated firing data are given for each charge equivalent in table V. The second column in table V gives the "charge ratio," defined as

$$\frac{\text{mass of propellant actually used}}{\text{mass needed to yield same } v_m \text{ in a closed-breech firing}} .$$

The numerator is 0.10582 kg in each case. The charge ratio gives an indication of the amount of available energy that is discharged through the vent. For comparison, a vented recoilless rifle[3] generally has a charge ratio of 2:3.

[3] *US Army Materiel Command, AMCP-706-150, Interior Ballistics of Guns, Ballistics Series, Engineering Design Handbook Series, Washington, DC (1965).*

TABLE V. ADDITIONAL CALCULATED FIRING DATA ON CHARGE EQUIVALENTS FOR BASIC CHARGE 9

Note: Elapsed times in milliseconds, measured from initiation of burning. t_s: start of motion; t_p: peak pressure attained; t_b: all-burned condition, i.e., propellant completely consumed; t_m: projectile exits muzzle.

Charge equivalent	Charge ratio	t_s ms	t_p ms	t_b ms	t_m ms
9	1.00	0.80	5.70	5.70	8.68
8	1.11	0.82	5.82	5.92	8.98
7	1.26	0.82	5.98	6.22	9.36
6	1.44	0.82	6.16	6.62	9.84
5	1.69	0.84	6.38	7.20	10.50
4	2.04	0.88	6.72	8.16	11.48
3	2.59	0.92	7.08	9.56	12.76
2	3.52	0.92	7.48	11.88	14.56
1	5.49	0.96	7.92	17.44	18.00
0	14.20	1.20	8.00	27.00	27.00

The next four columns of table V contain the elapsed time to each of the four "milestones" of the firing. In each case, t = 0 is the initiation of burning, and the four elapsed times correspond to

t_s - start of motion

t_p - peak pressure attained

t_b - propellant "all-burned"

t_m - muzzle exit.

A question raised in regard to the one-charge mortar is whether it is more sensitive to erratic propellant burning than is a closed-breech mortar (from COL J. A. Hatch, Ft Benning, GA). Erratic burning can be considered as a variation in the burning coefficient C_b. Its effect on muzzle velocity can be described by the percent change in v_m compared with the percent change in C_b. It is quite possible, and even likely, that C_b is not constant over the burning period, but the net effects of irregular burning can be treated by assuming that C_b is still constant, though altered in magnitude.

The percent changes in muzzle velocity were evaluated at several different charge equivalents, each in two cases: in case 1, C_b increased by 10 percent, and in case 2, C_b decreased by 10 percent. (The latter is a more likely occurrence, since it could correspond to incomplete or uneven ignition of the charge.) The results are given in table VI. They show that the open vents increase slightly the sensitivity to variations in C_b. Except at the largest area considered,

TABLE VI. EFFECT OF VARIATIONS IN BURNING RATE ON MUZZLE VELOCITY

Charge equivalent	δC_b (%)	δv_m Vented mortar with basic charge 9 (%)	δv_m for closed-breech mortar (%)
9	+10	+1.45	+1.45
	-10	-2.44	-2.44
6	+10	+2.05	+1.68
	-10	-2.93	-2.52
3	+10	+2.85	+2.53
	-10	-5.23	-3.60
1	+10	+8.01	+2.83
	-10	-15.13	-3.99

the increase is not large and probably would not cause any noticeable problem. It is not claimed that 10 percent is a "typical" value of deviation: it was chosen only as a round number to permit consistent comparisons. In most cases, the percentage change in v_m is less than the percentage change in C_b, indicating the muzzle velocity is not particularly sensitive to burning rate. In field use of mortars, in fact, errors caused by irregularities in muzzle velocity ("consistency") are far outweighed by errors in targeting ("accuracy").

3.3 Other Design Considerations

Shape of vent slot.--It was pointed out in connection with figure 3 that at high charge equivalents, a relatively small change in A* is sufficient to change v_m substantially. This has a bearing on the desired shape of the variable vent slot. As the vent gate is moved in its arcuate path, it will probably be provided with detents or gradations to indicate the charge equivalents (or perhaps muzzle velocity). A flared shape to the slot, permitting these gradations to be more or less evenly spaced, is illustrated in figure 6. The figures show two vent slots of equal area and equal overall length, one rectangular and one triangular. Although neither shape would be useful in practice, because of the sharp corners, it can be seen that the flared shape of the triangle lends some evenness to the detent spacing, while for the rectangular shape the higher charge equivalents are bunched together. With the more even spacing, the mortarman can move the handle rapidly into the desired position.

Mechanical design of vent gate.--The idea of a vented combustion chamber is not new, for as we have mentioned, vents are an established and successful element in recoilless rifle design. However, the open vent mortar contains moving parts that are exposed to the combustion chamber, which introduces some new factors. The vent gate, when in the closed position, must withstand the maximum blast, which is equal to that of a closed-breech mortar.

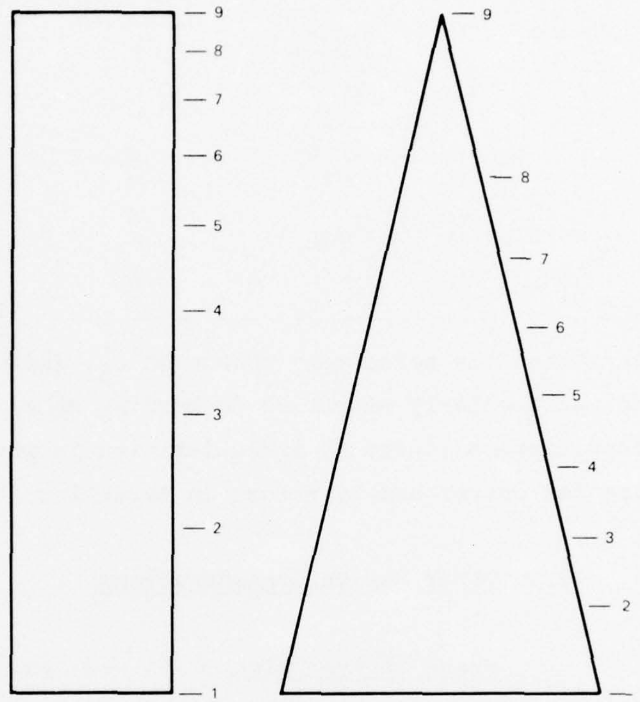

Figure 6. Rectangular- and triangular-shaped slots, showing positions for charge equivalents 1 (fully open) through 9 (fully closed). Each has a total area of 14.8 cm^2. Scale: 2/1.

Since the vent gate mechanism is exposed to high temperatures, it must be of such material and shape that the handle itself does not become too hot for the operator's hand. Also, since thermal expansion is likely to take place, provision must be made to prevent seizing of the moving parts. Rollers on the sliding mechanism would be useful in this regard.

The gate handle can be set at the desired position either by detents at preselected locations, or by markings allowing the operator to select any position of the handle. In the latter, some sort of locking or hold-down mechanism is needed, so that the position cannot change during the shock and vibration of firing.

Exhaust tube configuration.--The hot gas which is exhausted through the vent expands into an annular duct and flows out to the atmosphere near the muzzle, as diagrammed in figure 1. The flow can be approximated as a reservoir with a converging-diverging nozzle feeding into a long duct of constant cross section. The idealized situation is treated by Shapiro,[5] where he points out that many different flow regimes are possible, depending on the area ratio and pressure ratio involved.

The cross section of the annulus must be greater than the maximum vent area, perhaps twice as large. The outer tube may be thinner than the firing tube, since the contained pressure is less. The firing tube of present 81-mm mortars has an outside diameter of 95 mm, or a wall thickness of 7 mm (0.27 in.).

Evaluation of one-charge, variable-vent mortar system.--The one-charge mortar system is proposed as an alternative to the present system, a closed-breech mortar with ammunition having removable charge increments. However, the new system does require a mortar of somewhat greater weight and complexity. The present section will discuss some of this system's advantages.

The removal of excess charge increments has often posed difficulties in the field.[6,7] The problem is accentuated under difficult conditions, such as during night missions or very cold weather. At times, the ammunition handler must use valuable time to reattach a loose increment. With the one-charge, variable-vent mortar system, there is no need to strip the ammunition of excess charge

---

[5] A. H. Shapiro, *The Dynamics and Thermodynamics of Compressible Fluid Flow*, Ronald Press, New York (1953).

[6] Harold Chainin and Robert Kantenwein, *Improved Propellant Increment Holders for 81-mm Mortar Ammunition*, Picatinny Arsenal TR-3730, Dover, NJ (May 1968).

[7] Aberdeen Proving Ground, US Army Test and Evaluation Command, MTP4-2-012, *Commodity Engineering Test Procedure* (2 August 1971).

increments. This is especially advantageous when a series of rounds is fired at less than full charge, since the manual stripping of each individual round is eliminated. A single adjustment of the handle before the first round is fired suffices. This permits a more rapid rate of fire. Since the charges are not required to be flexible or removable, they can be sealed and made highly waterproof and resistant to physical damage.

The problem of disposal of unused increments is likewise eliminated. At present, unused increments are carried to a clear area and burned on the ground, as described in the infantry field manual.[8] This is done to avoid their being used by the enemy and to prevent an unsafe accumulation of increments near the mortar position. In the one-charge system, the full charge is burned upon firing, and no solid propellant is left.

4. CONCLUSIONS

The theory of the internal ballistics of the one-charge, variable-vent mortar has been derived from basic physical principles. One particular application, the 81-mm infantry mortar, has also been considered.

The study has shown that a mortar with an adjustable vent area can use a single-charge cartridge to replace the existing series of charges, 1 through 9. The vent areas needed to yield the desired muzzle velocities have been given in table III. It has been shown that the mortar tube experiences roughly the same temperatures and pressures as existing closed-breech systems.

---

[8] *Department of the Army, 81-mm Mortar, Field Manual FM 23-90 (1972); Revised (July 1975).*

Some of the advantages and disadvantages of the one-charge system have been discussed at appropriate points. Basically, it can be said that the one-charge system is somewhat costlier and more complex in its construction, but simpler and more efficient in its use.

It is recommended that the next phase of this project be the mechanical design of the tube with a variable vent, followed by field testing of the one-charge mortar system.

NOMENCLATURE

A	bore area
A^*	vent area
B	burning rate constant
C_b	coefficient of burning
C_f	coefficient of friction
M_p	initial mass of solid propellant
M_{pr}	mass of propellant remaining
M_R	mass of projectile
P	pressure
P_{atm}	atmospheric pressure
P_o	stagnation pressure
P_s	starting pressure
R	gas constant of combustion products
S	surface area of solid propellant
T	temperature
T_o	stagnation temperature
T_v	adiabatic isochoric flame temperature of solid propellant
V	volume
V_o	free chamber volume
x	projectile position
c_p	constant-pressure specific heat
c_v	constant-volume specific heat
e	energy released by combustion per unit mass of propellant

NOMENCLATURE (Cont'd)

f	function
h	enthalpy per unit mass
m	mass
$\dot{m}_b$	mass burned per unit time
$\dot{m}_d$	mass discharged per unit time
t	time
δ_t	increment of time
t_b	elapsed time to burning completion
t_m	elapsed time to muzzle exit
t_p	elapsed time to pressure peak
t_s	elapsed time to start of motion
u	internal energy per unit mass
v	velocity
v_m	muzzle velocity
x	travel (projectile displacement)
x_m	travel to muzzle
α	exponent of pressure dependence
γ	c_p/c_v
η	covolume of gas
ρ	density of solid propellant
ψ	coefficient of flow through vent

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(3) U.S. Army Materiel Command, AMCP-706-150, Interior Ballistics of Guns, Ballistics Series, Engineering Design Handbook Series, Washington, DC (1965).

(4) Leo D. Heppner, Final Report on Special Study of Setback and Spin for Artillery, Mortar, Recoilless Rifle, and Tank Ammunition, Aberdeen Proving Ground (1968).

(5) A. H. Shapiro, The Dynamics and Thermodynamics of Compressible Fluid Flow, Ronald Press, New York (1953).

(6) Harold Chainin and Robert Kantenwein, Improved Propellant Increment Holders for 81-mm Mortar Ammunition, Picatinny Arsenal TR-3730, Dover, NJ (May 1968).

(7) Aberdeen Proving Ground, US Army Test and Evaluation Command, MTP4-2-012, Commodity Engineering Test Procedure (2 August 1971).

(8) Department of the Army, 81-mm Mortar, Field Manual FM 23-90 (1972); Revised (July 1975).

APPENDIX A.--COMPUTER PROGRAM FOR SOLVING GOVERNING EQUATIONS

This appendix presents a FORTRAN program for solving the governing equations of a mortar with an open vent. It also gives a sample output for the 81-mm mortar with 5-cm^2 vent area.

OS/360 FORTRAN H EXTENDED PLUS

```
REQUESTED OPTIONS:

OPTIONS IN EFFECT:  NAME(MAIN) NOOPTIMIZE LINECOUNT(60) SIZE (0500K) AUTODBL (NONE)
                    SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT NOGOSTMT
                    NOXREF NOALC NOANSF NOTERMINAL FLAG (I)
                    FUNCTIONS INLINE ARE:  NONE

C                        THE FOLLOWING PROGRAM SOLVES THE GOVERNING EQUATIONS
C                        OF THE OPEN-VENT MORTAR
                    REAL MR,MP,M,MDOTB,MDOTD,MPR
                    FMDOTD(P,T)=PSI*ASTAR*(P-100000.)/SQRT(R*T)
C                        COEFFICIENT OF BURNING IS CBA
                    FMDOTB(P)=CBA*(P**0.8)
                    FDXDT(V)=V
C                        COEFFICIENT OF FRICTION IS CBB
                    FDVDT(P)=P*A/(MR*(1.+CBB))
                    FDMDT(MDOTB,MDOTD)=MDOTB-MDOTD
                    FDTDT(P,T,M,MDOTB,MDOTD)=(MDOTB*CV*(TV-T)-MDOTD*R*T-P*A*V)
                    /(CV*M)
                    FDMPR(MDOTB)=0.-MDOTB
C                        VALUES FOR 81 MM MORTAR
                    DATA VOLO,A,XM,MR/.001032,.005206,0.833,4.136/
C                        VALUES FOR M9 PROPELLANT
                    DATA TV,WTMOL,G,COVOL/3799.0,27.63,1.2102,.0009382/
                    UR=8.3143
                    R=UR/WTMOL*1000.
                    CV=R/(G-1.)
                    CP=CV+R
                    PSI=SQRT(G*((2./(G+1.))**((G+1.)/(G-1.))))
                    READ(5,601) MPCH,MP
                    NPRINT=15
C                        NC IS NUMBER OF RUNS
                    READ(5,603) NC
603                 FORMAT(I2)
                    DO 402 J=1,NC
                    WRITE(6,619) J
619                 FORMAT(//35X,'**********RUN NO.',I4,'**********')
C                        INITIAL VALUES
                    TIME=0.
                    X=0.
                    V=0.
                    P=100000.
                    T=300.
                    M=P*VOLO/R/T
```

```
C               MPR IS MASS OF PROPELLANT REMAINING
          MPR=MP
          TMAX=0.
          PMAX=0.
          READ(5,602) CBA,CBB,H,ASTAR
601       FORMAT(I1,F20,10)
602       FORMAT(4F20.10)
          CB=CBA*1000000.0
          WRITE(6,612)
612       FORMAT(/7X,'TIME',12X,'P',8X,'TRAVEL',9X,'VELOC',10X,'M',11X,
            'MPR',12X,'TEMP',7X,'MDOTB',9X,'DISCH'/)
          WRITE(6,610) TIME,P,X,V,M,MPR,T
          DO 400 I=1,600
          MDOTB=FMDOTB(P)
          MDOTD=FMDOTD(P,T)
C               FORWARD INTEGRATION BY EULER'S METHOD
          X=X+H*FDXDT(V)
          M=M+H*FDMDT(MDOTB,MDOTD)
          V=V+H*FDVDT(P)
C               STARTING PRESSURE FOR MOTION IS 700 KPA (100 PSI)
          IF(P .LT. 700000. .AND. V .LT. 10.) V=0.
          T=T+H*FDTDT(P,T,M,MDOTB,MDOTD)
          IF(T .GT. TMAX) TMAX=T
          TIME=TIME+H
C               EQUATION OF STATE WITH COVOLUME TERM
          P=M*R*T/(VOLO+A*X-M*COVOL)
          IF(P .GT. PMAX) TPMAX=TIME
          IF(P .GT. PMAX) PMAX=P
          MPR=MPR-H*MDOTB
          IF(V .LT. 0.0001) TSTART=TIME
          IF( MPR .LE. 0.000001) MPR=0.
          IF( MPR .LE. 0.000001) CBA=0.
          IF( MPR .GT. 0.000001) TBURN=TIME
          IF(X .GT. XM) GO TO 401
          IF(NPRINT * (I/NPRINT) .NE. I) GO TO 403
          WRITE(6.610) TIME,P,X,V,M,MPR,T,MDOTB,MDOTD
403       CONTINUE
400       CONTINUE
401       CONTINUE
          VM=V
C               WARNING IN CASE OF INSUFFICIENT STEPS
          IF( X ,LT, (XM-0,01)) VM=0.
C               WARNING IN CASE OF INCOMPLETE BURNING
          IF( MPR .GT. 0.000001) TBURN=888888.88
          WRITE(6,610) TIME,P,X,V,M,MPR,T,MDOTB,MDOTD
610       FORMAT( 6X,F7.5,E14.3,F12.3,F13.2,F14.5,F14.5,F14.1,2F14.3)
          PMAX=PMAX/1000000.
          WRITE(6.618) MPCH,ASTAR
618       FORMAT*/'**BASIC CHARGE LEVEL',I2,8X,'VENT AREA',F9.6)
          WRITE(6,620) CB,CBB,H
```

```
620        FORMAT(/'**CB',F5.1,'*10**-6',8X,'CF',F6.3,8X,'STEP SIZE',F8.5)
           WRITE(6.616) VM,PMAX,TMAX
616        FORMAT(/'**RESULTS** MUZZLE VELOCITY',F7.2,8X,'MAX PRESSURE',
            F6.2,' MPA',8X,'MAX TEMP',F7.1)
           WRITE(6,617) TSTART,TPMAX,TBURN,TIME
617        FORMAT(/'**MILESTONES**START',F8.5,8X,'PRESSURE PEAK',F8.5,
            8X,'BURN-OUT',F8.5,8X,'MUZZLE EXIT',F8.5//)
402        CONTINUE
           STOP
           END

*OPTIONS IN EFFECT*NAME(MAIN) NOOPTIMIZE LINECOUNT(60) SIZE(0500K) AUTODBL(NONE)
*OPTIONS IN EFFECT*SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT NOGOSTMT
 NOXREF NOALC NOANSF NOTERMINAL FLAG(I)
*OPTIONS IN EFFECT*FUNCTIONS INLINE ARE: NONE
*OPTIONS IN EFFECT*
*STATISTICS*  SOURCE STATEMENTS = 91, PROGRAM SIZE = 2568, SUBPROGRAM NAME = MAIN
*STATISTICS* NO DIAGNOSTICS GENERATED
```

APPENDIX A

RUN NO. 1

TIME	P	TRAVEL	VELOC	M	MPR	TEMP	MDOTB	DISCH
0.0	0.100E+06	0.0	0.0	0.00114	0.10582	300.0		
0.00030	0.225E+06	0.0	0.0	0.00124	0.10570	619.9	0.506E+00	0.880E-01
0.00060	0.443E+06	0.0	0.0	0.00141	0.10550	1075.2	0.874E+00	0.189E+00
0.00090	0.785E+06	0.000	0.05	0.00168	0.10516	1604.7	0.139E+01	0.311E+00
0.00120	0.129E+07	0.000	0.41	0.00208	0.10463	2117.9	0.207E+01	0.471E+00
0.00150	0.198E+07	0.000	0.98	0.00266	0.10388	2547.5	0.293E+01	0.681E+00
0.00180	0.289E+07	0.001	1.84	0.00346	0.10284	2871.1	0.398E+01	0.956E+00
0.00210	0.406E+07	0.001	3.06	0.00450	0.10145	3098.6	0.523E+01	0.131E+01
0.00240	0.550E+07	0.003	4.74	0.00584	0.09965	3251.6	0.668E+01	0.174E+01
0.00270	0.722E+07	0.004	6.99	0.00750	0.09739	3351.1	0.832E+01	0.227E+01
0.00300	0.923E+07	0.007	9.90	0.00950	0.09461	3413.5	0.101E+02	0.288E+01
0.00330	0.115E+08	0.010	13.57	0.01188	0.09125	3450.2	0.121E+02	0.358E+01
0.00360	0.139E+08	0.015	18.09	0.01464	0.08730	3469.1	0.141E+02	0.435E+01
0.00390	0.165E+08	0.021	23.51	0.01778	0.08272	3475.2	0.162E+02	0.517E+01
0.00420	0.191E+08	0.029	29.86	0.02129	0.07752	3472.1	0.183E+02	0.600E+01
0.00450	0.216E+08	0.039	37.13	0.02515	0.07173	3462.0	0.202E+02	0.681E+01
0.00480	0.239E+08	0.051	45.27	0.02932	0.06540	3446.6	0.219E+02	0.756E+01
0.00510	0.259E+08	0.066	54.17	0.03375	0.05859	3427.2	0.234E+02	0.822E+01
0.00540	0.275E+08	0.084	63.72	0.03839	0.05139	3404.9	0.245E+02	0.877E+01
0.00570	0.287E+08	0.104	73.76	0.04319	0.04389	3380.4	0.254E+02	0.919E+01
0.00600	0.294E+08	0.128	84.16	0.04809	0.03619	3354.7	0.259E+02	0.947E+01
0.00630	0.297E+08	0.154	94.75	0.05305	0.02836	3328.2	0.262E+02	0.963E+01

RUN NO. 1 (Cont'd)

TIME	P	TRAVEL	VELOC	M	MPR	TEMP	MDOTB	DISCH
0.00660	0.298E+08	0.184	105.41	0.05801	0.02050	3301.5	0.262E+02	0.968E+01
0.00690	0.295E+08	0.217	116.02	0.06295	0.01266	3275.1	0.260E+02	0.963E+01
0.00720	0.290E+08	0.254	126.49	0.06783	0.00491	3249.3	0.257E+02	0.951E+01
0.00750	0.271E+08	0.293	136.70	0.07012	0.0	3204.0	0.0	0.904E+01
0.00780	0.234E+08	0.335	145.76	0.06760	0.0	3122.8	0.0	0.789E+01
0.00810	0.203E+08	0.380	153.61	0.06539	0.0	3047.2	0.0	0.693E+01
0.00840	0.178E+08	0.427	160.44	0.06344	0.0	2977.1	0.0	0.612E+01
0.00870	0.157E+08	0.476	166.44	0.06171	0.0	2912.1	0.0	0.545E+01
0.00900	0.139E+08	0.527	171.74	0.06017	0.0	2851.9	0.0	0.488E+01
0.00930	0.124E+08	0.579	176.45	0.05879	0.0	2796.0	0.0	0.439E+01
0.00960	0.111E+08	0.633	180.67	0.05754	0.0	2743.9	0.0	0.397E+01
0.00990	0.100E+08	0.687	184.46	0.05641	0.0	2695.4	0.0	0.361E+01
0.01020	0.911E+07	0.743	187.90	0.05538	0.0	2650.1	0.0	0.330E+01
0.01050	0.830E+07	0.800	191.02	0.05443	0.0	2607.7	0.0	0.303E+01
0.01068	0.787E+07	0.835	192.76	0.05390	0.0	2583.6	0.0	0.288E+01

**BASIC CHARGE LEVEL 9 VENT AREA 0.000500

CB 27.5*10-6 CF 0.055 STEP SIZE 0.00002

RESULTS MUZZLE VELOCITY 192.76 MAX PRESSURE 29.79 MPA MAX TEMP 3475.3

MILESTONES START 0.00084 PRESSURE PEAK 0.00646 BURN-OUT 0.00738 MUZZLE EXIT 0.01068

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